Leveraging a functional 🤖 approach for easier testing and maintenance of ROS 2 code

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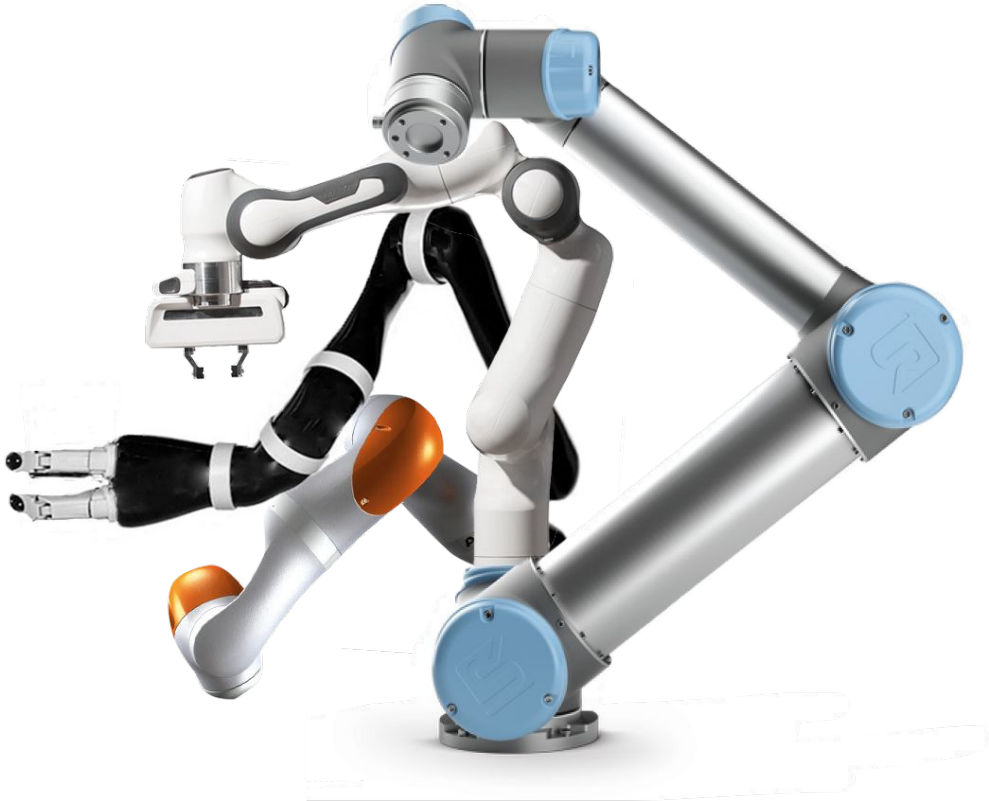
Outline

- Introduction
- ROS 2 Conventional Approach
- Introduction to Functional Programming Principles
- Refactoring using Functional Programming Principles
- Conclusion



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Introduction

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About Me

- Robotics Engineer on the services team at PickNik Robotics
  - Contributed to a wide variety of client projects: remotely operated underwater inspection vehicles, autonomous mobile base for agriculture applications, and more
- Have worked at General Dynamics Electric Boat, MIT Lincoln Laboratory
- Interested in robotics since high school

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- ROS 2 documentation encourages an object-oriented paradigm that can lead to trouble writing code that achieves the goal
- **Adopting functional programming techniques into our code has made it easier to test, maintain, and extend code!**

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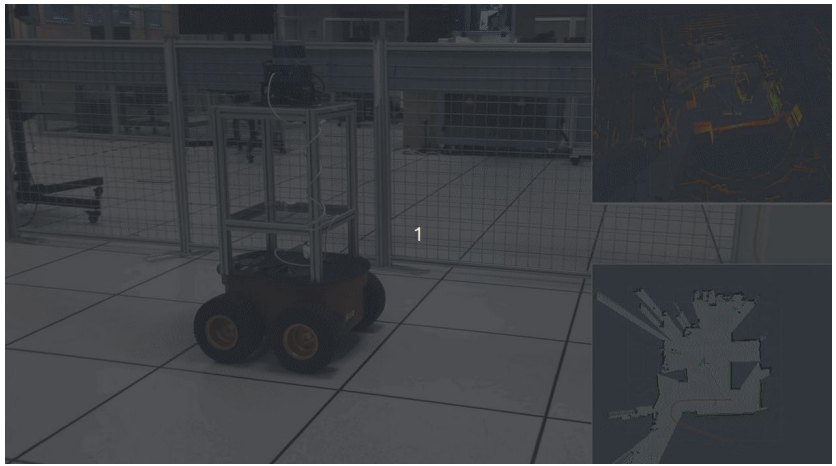
Motivating Example

- Problem: A robot wants to navigate from its current location to some goal



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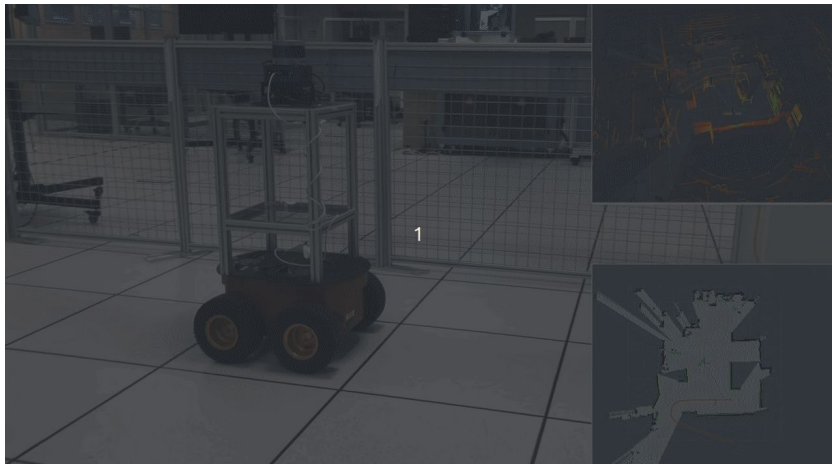

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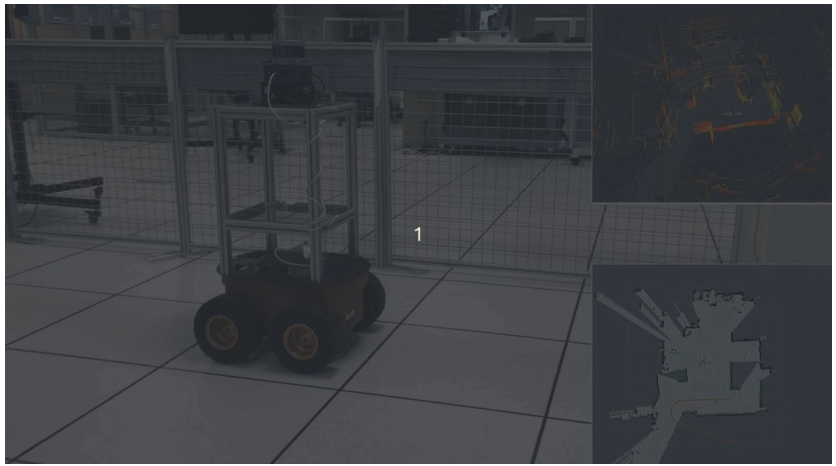

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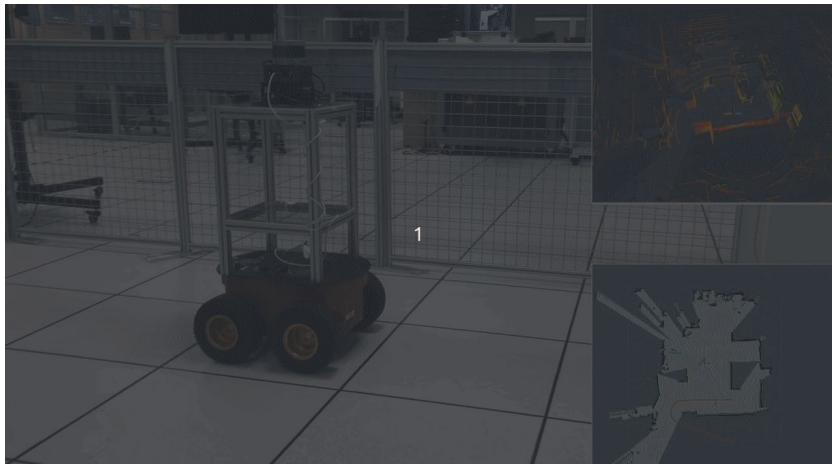

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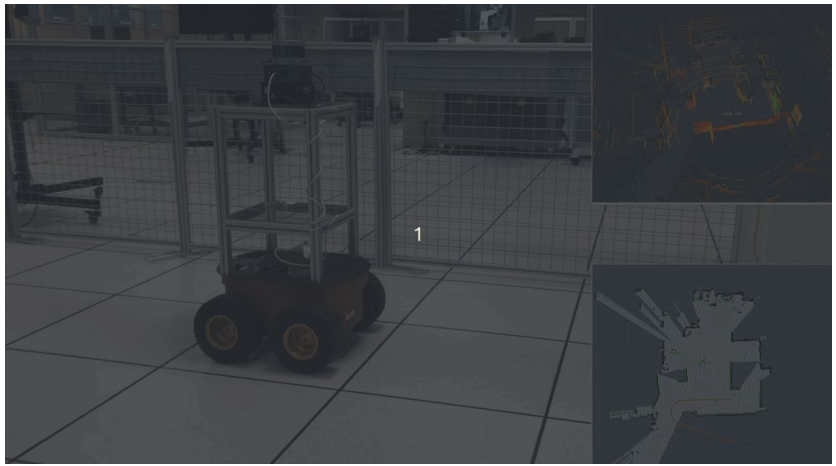
- The robot needs to know where obstacles are located in its environment
- Let's use an occupancy map to represent the environment
- Assumption: The robot knows its location in the occupancy map at all times
- Solution: The robot will send a request to a ROS 2 service that generates a path from the robot's current location and goal location, given an occupancy map



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  Map<unsigned char> map_;
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- `PathGenerator` will be used to generate the path for our robot
- This code was written using example code available from the ROS 2 documentation
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- **Involving inter-process communication in unit tests introduces flakiness**
- Is there a way to refactor this code such that invoking the ROS 2 API is avoided?
- Yes, by using functional programming principles

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Introduction to Functional Programming Principles

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- Let's go over some principles and see how we can use them in refactoring `PathGenerator`

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- A function is pure if and only if it could be replaced by a lookup table (potentially infinitely large!)

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  - std::transform, std::find_if, std::copy, and more

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  - Error Propagation: Errors can be automatically propagated through a sequence of computations until they are explicitly handled

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- Let's try and refactor `PathGenerator`
    - **Claim: that the refactored `PathGenerator` has 100% coverage**

Refactoring using Functional Programming Principles

Refactoring PathGenerator

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 public:
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- How the current `PathGenerator` looks

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- The private functions of `PathGenerator` can be turned into free functions and lambda functions
- Let's refactor the callback function for the generate path service

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```
void generate_path_service(
const std::shared_ptr<GetPath::Request> request,
      std::shared_ptr<GetPath::Response> response) {
  if (map_.get_data().size() == 0) {
    RCLCPP_ERROR_STREAM(this->get_logger(), "MAP IS EMPTY!!");
    response->code.code = example_srvs::msg::GetPathCodes::EMPTY_OCCUPANCY_MAP;
    response->path = std_msgs::msg::UInt8MultiArray();
    return;
  }
  /* More error pre-checks */

  auto const start = Position{request->start.data[0], request->start.data[1]};
  auto const goal = Position{request->goal.data[0], request->goal.data[1]};

  // Generate the path
  auto const path = generate_global_path(start, goal);

  // Start populating the response message
  auto response_path = std_msgs::msg::UInt8MultiArray();

  /* Code about populating the message here */

  response->code.code = !path.empty() ? example_srvs::msg::GetPathCodes::SUCCESS :
example_srvs::msg::GetPathCodes::NO_VALID_PATH;
    response->path = response_path;
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    RCLCPP_ERROR_STREAM(this->get_logger(), "MAP IS EMPTY!!");
    response->code.code = example_srvs::msg::GetPathCodes::EMPTY_OCCUPANCY_MAP;
    response->path = std_msgs::msg::UInt8MultiArray();
    return;
  }
  /* More error pre-checks */

  auto const start = Position{request->start.data[0], request->start.data[1]};
  auto const goal = Position{request->goal.data[0], request->goal.data[1]};

  // Generate the path
  auto const path = generate_global_path(start, goal);

  // Start populating the response message
  auto response_path = std_msgs::msg::UInt8MultiArray();

  /* Code about populating the message here */

  response->code.code = !path.empty() ? example_srvs::msg::GetPathCodes::SUCCESS :
example_srvs::msg::GetPathCodes::NO_VALID_PATH;
    response->path = response_path;
  }
```

- `generate_path_service` is:
  - printing errors

PICKNIK

Refactoring PathGenerator

```
void generate_path_service(
const std::shared_ptr<GetPath::Request> request,
      std::shared_ptr<GetPath::Response> response) {
  if (map_.get_data().size() == 0) {
    RCLCPP_ERROR_STREAM(this->get_logger(), "MAP IS EMPTY!!");
    response->code.code = example_srvs::msg::GetPathCodes::EMPTY_OCCUPANCY_MAP;
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- `generate_path_service` is:
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  - generating the path

PICKNIK

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void generate_path_service(
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- `generate_path_service` is:
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  - generating the path
  - setting an out parameter

PICKNIK

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- `generate_path_service` is:
  - printing errors
  - generating the path
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- Let's isolate the error printing functionality to another function
  - The error printing function needs to be passed an error type

PICKNIK

Refactoring PathGenerator

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- `generate_path_service` is:
  - printing errors
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- Let's isolate the error printing functionality to another function
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- The object held by the shared pointer can be assigned by another function

PICKNIK

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- `generate_path_service` is:
  - printing errors
  - generating the path
  - setting an out parameter
- Let's isolate the error printing functionality to another function
  - The error printing function needs to be passed an error type
- The object held by the shared pointer can be assigned by another function
- The `generate_global_path` function and associated pre-checks can be extracted to another function

PICKNIK

Refactoring PathGenerator

```
std::expected<GetPath::Response, error> generate_path(
  std::shared_ptr<GetPath::Request> const request,
  Map<unsigned char> const& occupancy_map, PathingGenerator path_generator) {
  if (occupancy_map.get_data().size() == 0) {
    return std::unexpected(error::EMPTY_OCCUPANCY_MAP);
  }
  /* More error pre-checks */

  auto const start = Position{request->start.data[0], request->start.data[1]};
  auto const goal = Position{request->goal.data[0], request->goal.data[1]};

  // Generate the path using the path generator function that was input
  auto const path = path_generator(start, goal, occupancy_map);
  if (!path.has_value()) {
    return std::unexpected(error::NO_VALID_PATH);
  }

  auto response = GetPath::Response{};
  /* More implementation code */
  return response;
}
```

- Here is the refactored core functionality of the generate path callback

PICKNIK

Refactoring PathGenerator

```
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- Here is the refactored core functionality of the generate path callback
- This function returns a type which can be used for **monadic error handling**

PICKNIK

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- Here is the refactored core functionality of the generate path callback
- This function returns a type which can be used for **monadic error handling**
- If there is an error, the function can handle the error in a compile time checkable way

PICKNIK

Refactoring PathGenerator

```
using PathingGenerator = std::function<std::optional<Path>(
    Position const&, Position const&, Map<unsigned char> const&)>;

std::expected<GetPath::Response, error> generate_path(
  std::shared_ptr<GetPath::Request> const request,
  Map<unsigned char> const& occupancy_map, PathingGenerator path_generator) {
  if (occupancy_map.get_data().size() == 0) {
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- Here is the refactored core functionality of the generate path callback
- This function returns a type which can be used for **monadic error handling**
- If there is an error, the function can handle the error in a compile time checkable way
- The function that generates the path can now be passed in, making this function a **higher order function**

PICKNIK

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- If there is an error, the function can handle the error in a compile time checkable way
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- This function is deterministic and has no side effects, so it is a **pure function**

PICKNIK

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- Here is the refactored core functionality of the generate path callback
- This function returns a type which can be used for **monadic error handling**
- If there is an error, the function can handle the error in a compile time checkable way
- The function that generates the path can now be passed in, making this function a **higher order function**
- This function is deterministic and has no side effects, so it is a **pure function**
- Let's test this function

PICKNIK

Testing the Refactored PathGenerator

```
TEST(GeneratePath, NoValidPath) {
  // GIVEN a GetPath request and an occupancy map
  auto const sample_occupancy_map = get_test_occupancy_map();

  auto const request = std::make_shared<GetPath::Request>();

  request->start.data = {2, 2};
  request->goal.data = {5, 5};

  // WHEN the path is requested
  auto const response = pathing::generate_path::generate_path(
      request, sample_occupancy_map, pathing::generate_global_path);

  // THEN there should be an error with the error::NO_VALID_PATH type
  EXPECT_EQ(response.error(), pathing::generate_path::error::NO_VALID_PATH);
}
```


PICKNIK

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```

- Testing the refactored functionality is trivial

PICKNIK

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- Testing the refactored functionality is trivial
  - Create required parameters

PICKNIK

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- Testing the refactored functionality is trivial
  - Create required parameters
  - Pass the parameters into the function under test

PICKNIK

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PICKNIK

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- All the functions that have been refactored so far can be tested this way

PICKNIK

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- Testing the refactored functionality is trivial
  - Create required parameters
  - Pass the parameters into the function under test
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- All the functions that have been refactored so far can be tested this way
- Everything can now be put together for the callback being executed by the generate path service

PICKNIK

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- Testing the refactored functionality is trivial
  - Create required parameters
  - Pass the parameters into the function under test
  - Check the return
- All the functions that have been refactored so far can be tested this way
- Everything can now be put together for the callback being executed by the generate path service
- **All of this has been done without invoking the ROS 2 API!**

PICKNIK

Putting it all together

```
[this](auto const request, auto response) {
    auto const print_error = [this](std::string_view error)
        -> std::expected<GetPath::Response, std::string> {...};

    auto const return_empty_response = []([[maybe_unused]] auto const)
        -> std::expected<GetPath::Response, std::string> {...};

    auto const stringify_error = [](auto const error) {...};

    *response = generate_path::generate_path(request, this->map_,
generate_global_path)
            .map_error(stringify_error)
            .or_else(print_error)
            .or_else(return_empty_response)
            .value();
  }
```

- The generate path callback function has been replaced by a lambda function

PICKNIK

Putting it all together

```
[this](auto const request, auto response) {
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            .value();
  }
```

- The generate path callback function has been replaced by a lambda function
- If `generate_path` returns the expected value, it is directly assigned to `response`

PICKNIK

Putting it all together

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```

- The generate path callback function has been replaced by a lambda function
- If `generate_path` returns the expected value, it is directly assigned to `response`
- If `generate_path` returns an error, the error is handled by chaining functions together
    - This is the result of returning a monadic type and performing monadic error handling

PICKNIK

Putting it all together

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- The generate path callback function has been replaced by a lambda function
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- If needed, more functions can be added to manipulate the expected type or error type, increasing modularity

PICKNIK

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```

- The generate path callback function has been replaced by a lambda function
- If `generate_path` returns the expected value, it is directly assigned to `response`
- If `generate_path` returns an error, the error is handled by chaining functions together
  - This is the result of returning a monadic type and performing monadic error handling
- If needed, more functions can be added to manipulate the expected type or error type, increasing modularity
- How can this lambda be tested?

PICKNIK

DI and Functional Programming

```
template <typename ServiceType>
using ServiceCallback =  std::function<void(
        std::shared_ptr<typename ServiceType::Request>const ,
        std::shared_ptr<typename ServiceType::Response>)>;

struct Manager {
  struct MiddlewareHandle {
    // Define map service callback type
    using SetMapCallback = ServiceCallback<SetMap>;

    // Define path generation service callback type
    using GeneratePathCallback = ServiceCallback<GetPath>;

    virtual ~MiddlewareHandle() = default;

    virtual void register_set_map_service(SetMapCallback callback) = 0;

    virtual void register_generate_path_service(GeneratePathCallback callback) = 0;

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DI and Functional Programming

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- This abstract interface can be used to implement each function using the ROS API

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- This abstract interface can be used to implement each function using the ROS API
- The lambda function that is used for the generate path service can be captured via mocking and tested

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Testing with DI

```
struct PathManagerFixture : public testing::Test {
  PathManagerFixture() : mw_{std::make_unique<MockMiddlewareHandle>()} {
    // When the map callback is called, set the costmap
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TEST_F(PathManagerFixture, NoPath) {
  // GIVEN a path generator with a costmap
  auto const path_generator = pathing::Manager{std::move(mw_)};
  // WHEN the generate path service is called with an unreachable goal
  auto path_request = std::make_shared<GetPath::Request>();
  path_request->start.data = {2, 2};
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- **There was no invocation of the middleware using DI and all code is testable without invoking the ROS 2 API!**

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- Using higher order functions increased the modularity of the code, in this case allowing for different path generating algorithms to be used
- Monadic error handling led to easier error checking
- Refactoring `PathGenerator` using DI in conjunction with the functional programming paradigm led to code that has 100% coverage

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- Mariyum Gill
- Griswald Brooks
- Davide Faconti
- Kyle Kirves
- Tyler Weaver
- Chris Thrasher
- Brian Cairl
- Everyone else at PickNik

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Bilal Gill

Leveraging a Functional Approach for More Testable and Maintainable ROS 2 Code

Thank you!

All code and the full presentation are available at:

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